Presidential Address for 1998–1999

The Origin of Jenolan Caves: Elements of a New Synthesis and Framework Chronology

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Jenolan Caves are Australia's premier show caves. It has proved difficult to explain the origin and development of these caves. A new synthesis and framework chronology is proposed involving at least ten distinct phases of development beginning in the Carboniferous and extending until recent times.

Key elements of this new synthesis are Carboniferous and Permian palaeokarst, exhumation of palaeokarst, hydrothermal speleogenesis, the influence of steeply dipping limestone on morphology, complex hydrology, sediment blockages and paragenesis. Many significant features of the caves are not the products of solution by meteoric water.

This new synthesis and framework chronology challenges not only the accepted scientific view of the caves, but also the way in which they are conserved, managed and interpreted.

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INTRODUCTION

Jenolan Caves, located 100 km due west of Sydney (Fig. 1), are Australia's best-known and most-visited limestone caves. With a history of tourist development and conservation beginning in the 1860s, one might expect that their origin would have been the subject of much speculation, research and publication. Surprisingly this is not the case. While there has been a significant amount of work on the palaeontology and structure of the Late Silurian Jenolan Caves Limestone, and some speculation on the age of the caves (e.g. Sussmilch and Stone 1915), there has been little or no serious consideration given to how the caves formed.

The most widely known explanation for the origin of the caves is found in the eleven editions of Dunlop's guidebook published between 1950 and 1979. In summary, Dunlop stated that, "The caves owe their existence to the two facts that calcium carbonate.... dissolves slightly in river waters and the limestone.... is traversed by fine cracks.... which admit water to all parts of the rock and thus enable solution to proceed" [p 18] and "the caves are the channels of three streams which flow through the limestone" [p 23] (Dunlop, 1979).

Much of the more scientific discussion that has occurred to date is to be found in Steve McClean's unpublished honours thesis (McClean 1983) and in the unpublished

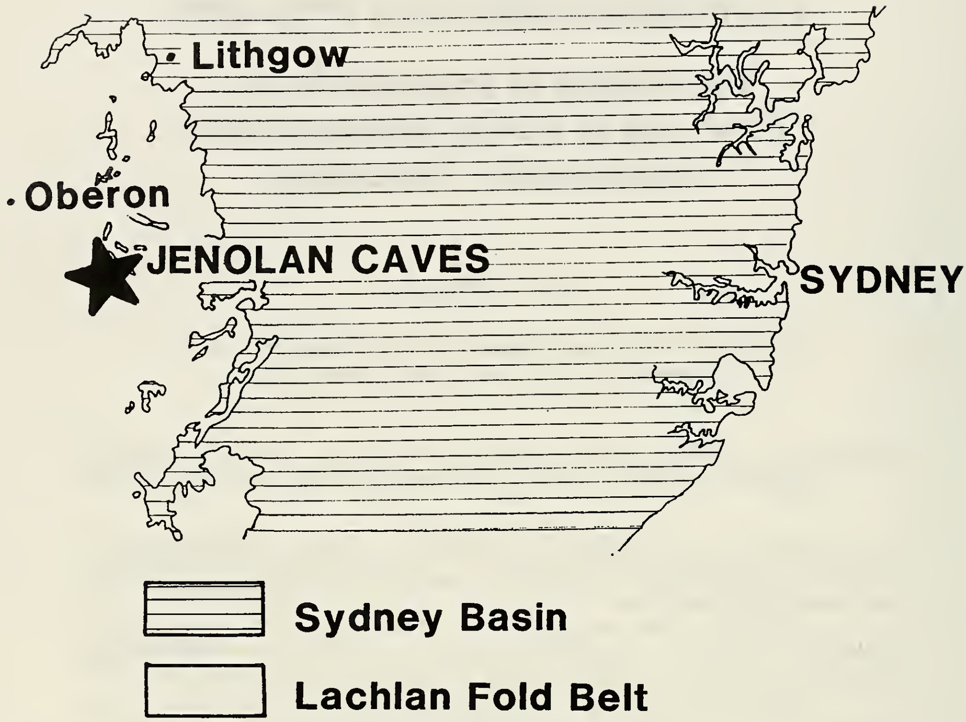

Figure 1. Location of Jenolan Caves

portions of my own PhD thesis (Osborne 1987). Kiernan (1988a) provided a good summary of the various karst features at Jenolan and the role of geological structure in guiding their development. He only gave a brief account of the evidence for the origin and development of the caves, noting that "in the absence of a suitable map the origin of the caves has not yet been fully resolved".

My own published work has largely concentrated on palaeokarst at Jenolan and its likely age and role in cave development (Osborne 1984, 1991, 1993, 1995). I have only discussed possible mechanisms of cave development at Jenolan quite recently (Osborne 1996, 1999).

The general lack of attention to the problem of the origin and history of Jenolan Caves may be due to a number of factors. One was a management policy between 1915 and 1983 that kept scientists out of the show caves. Another was a serious lack of scientific interest in the science of caves in Australia. I believe, however, that an additional important factor has been the failure of conventional approaches to explain many of the significant features and characteristics observed at Jenolan.

FEATURES OF JENOLAN CAVES REQUIRING EXPLANATION

There are a number of features of the caves and surrounding landscape at Jenolan which cannot be accounted for by any simple interpretation of landform development, or by any single phase, entirely meteoric cave development process. Eight of these features are outlined below.

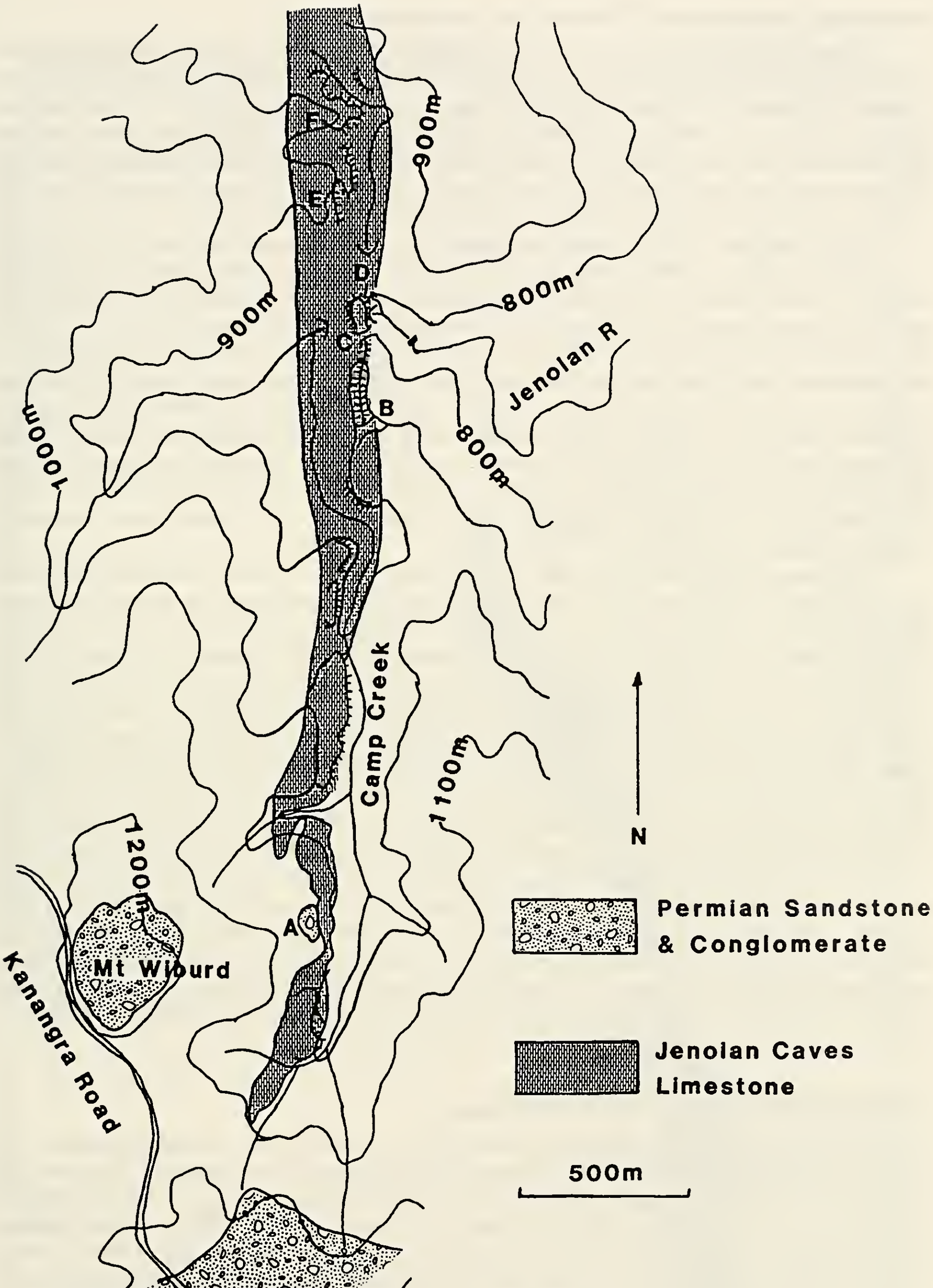

Figure 2. Evidence for landscape age; Camp Creek and Jenolan River South. A) Deposit of Permian conglomerate located within the valley of Camp Creek; B) Saddle south of Lucas Rocks; C) Saddle above Grand Archway; D) Carlotta Arch; E) 900 m bench at Jenolan Village; F) 900 m bench north of Jenolan Village.

Seemingly Contradictory Evidence For Landscape Age

Sussmilch and Stone (1915) provided the first reasoned approach to the question of cave and landscape ages at Jenolan. Using the then accepted timing for the uplift of the eastern Highlands (2 million years ago), Sussmilch and Stone applied a simple incision approach which led them to conclude that the highest levels of the present caves could be no more than 500,000 years old. A similar approach using modern incision rates derived from workers such as Bishop (1985) and Young (1977) would suggest that old high level caves, such as Carlotta Arch, could be at least eight million years old.

Field evidence, however, suggests that such simple approaches have little validity at Jenolan. Doughty (1994) found a conglomerate deposit in Camp Creek 1.9 km south of the Grand Archway. This deposit sits unconformably on the Jenolan Caves Limestone and has a base elevation of 1040 m, well within the valley of Camp Creek (A in Fig 2). The valley lip at that point is defined by the 1180 m contour. Doughty correlated these conglomerates with the Permian Snapper Point Formation, outliers of which are found at various levels in the landscape near Jenolan Caves (Gostin and Herbert 1973). Similar conglomerates with a base elevation of 1220 m occur 1.4 km further south near the Kanangra Walls Road (Fig. 2). If we assume that the base of these deposits approximates the gradient of a Permian valley floor and extrapolate north to near Lucas Rocks, a base elevation of 810 m would be expected, well below the 910 m elevation of the limestone outcrop forming Lucas Rocks.

Kiernan (1988a) and I (Osborne 1987) recognised two distinct erosional benches in the landscape at Jenolan Caves. The higher bench has an elevation of 900–930 m at Jenolan Village (E & F in Fig 2) and can be traced north, up the Jenolan River Valley. The lower bench has an elevation of approximately 830 m and includes the flat area near Carlotta Arch (D in Fig 2) and the saddle above the Grand Archway (C in Fig 2). The northward slope of the Permian base level between Kanangra Road and Doughty's outcrop would allow either or both of these benches to have Permian origins. North of Jenolan Caves the Jenolan River Valley has a distinct valley-in-valley structure. The 900 m bench forms the floor of the upper, broad valley, while the lower narrow valley results from incision below the 900 m bench. I (Osborne 1995) noted that Dreamtime Cave, developed below the 900 m bench, contains conglomerate likely to be of Permian age.

These observations suggest that a valley with a floor level at least as low as 900 m existed at Jenolan during the Permian and that the valley was filled, exhumed and then incised. It is clear, however, that the situation is not that simple. Resting on, and exposed in, the saddle above the Grand Archway are not only conglomerates of probable Permian age, but also what are clearly Cainozoic (probably Pleistocene) bone-bearing gravels. Any new synthesis must account for this and other seemingly contradictory occurrences.

Parallel Surface and Underground Drainage

One striking feature of Jenolan Caves is the development of parallel surface and underground drainage paths (both active and fossil) through the limestone. The semi-dry valleys of Camp Creek and Jenolan River are paralleled at a lower level by the conduits presently carrying underground drainage and at a higher level by both surface palaeochannels and underground palaeoconduits (air-filled and sediment-filled caves) (Fig. 3). Caves, some of which contain bone-bearing sediment, are intersected by the walls of the limestone gorges of the Jenolan River, upstream of the Devils Coach House.

Cave sediments containing large boulders indicate that at times in the past the northern show caves carried much of the flood load of the Jenolan River, while at present this flows overland, except for its short underground path through the Devils Coach House. Any new synthesis must account for the development of these parallel systems of drainage.

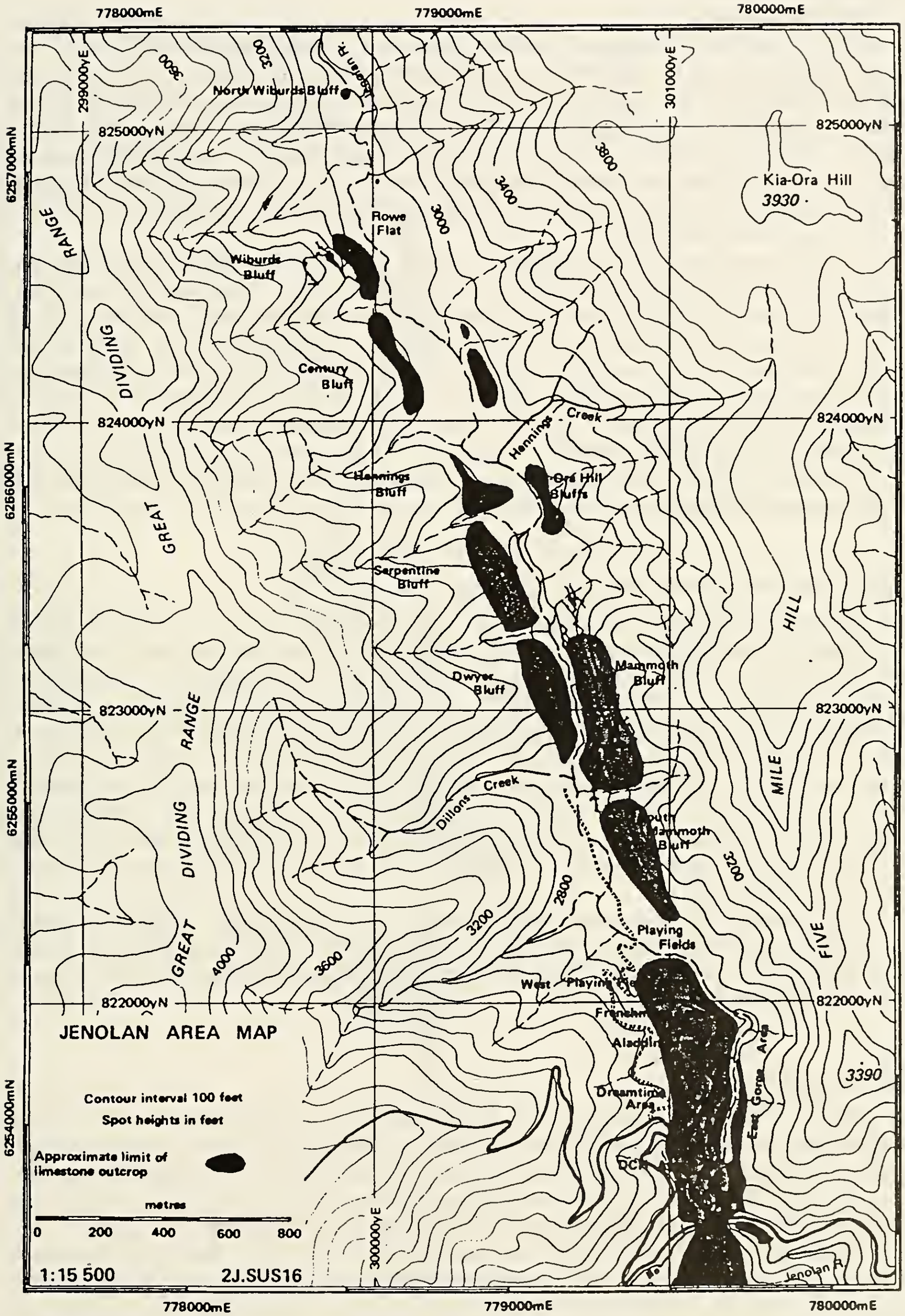

Figure 3. Caves and surface drainage, upstream of the Grand Archway, after Welch (1976).

Complex Drainage

Careful examination of cave maps, many years spent by cavers attempting unsuccessfully to find new sections of cave by following streams and the findings of cave divers all indicate that the geometric pattern and hydrology of Jenolan Caves is far from simple. It could in no way represent the simple path of three underground streams as suggested by Dunlop (1979). The more we know of present and past drainage, the more it becomes clear that pattern of drainage at Jenolan is quite complex and has been complex in the past. While there are stream passages in Jenolan Caves, and the caves do capture streams underground, the path of these streams and the passages in which they flow are neither simple nor continuous.

A good example of this situation has been the long search by cavers and cave divers for the section of the "Jenolan Underground River" known as the "Hairy Diprotodon" connecting Slug Lake in Mammoth Cave with the stream passage in Spider Cave. Although cavers, cave divers and geophysical investigations (T. Hubble, pers comm) have located cave passages in the area between the northern end of Spider Cave and the southern extremity of Mammoth Cave, there is no single large "river" passage linking Slug Lake with Spider Cave. The Jenolan Undergound River rather takes a complex route, in places reaching depths of more than 90 m below its surface level.

Any new synthesis must account for the development of complex drainage patterns and the presence of large chambers extending to great depths below the water table.

Exposure of Palaeokarst Deposits in Caves

Palaeokarst deposits at Jenolan Caves, and many other places in eastern Australia, are exposed in and intersected by caves. In some places palaeokarst deposits have guided cave development. This is unlike the situation described in the international literature and observed by me in 1997 during fieldwork in Europe (Bosak et al. 1989, Ford 1995 and Osborne in press). In many karst areas palaeokarst deposits are evident and often abundant as in the classical karst of Slovenia. There palaeokarst deposits are found exposed in natural outcrops at the surface, in quarry faces and in motorway cuttings, but rarely, if ever, are they exposed in caves. Ford (1995) noted that it was unusual for modern caves to intersect and exhume filled palaeokarst cavities, except where the modern caves were the result of *per ascensum* (caused by water rising from below) hydrothermal, artesian or stratiform karstification.

The presence of palaeokarst in the Jenolan Caves Limestone is neither surprising nor difficult to explain, however, the exposure of palaeokarst and the role it has played in guiding cave development in Jenolan Caves does require explanation and must be addressed in any new synthesis.

Cupolas and Halls

Some of the most striking morphological features of Jenolan Caves are the large dome-shaped chambers (cupolas) found in the southern show caves (Temple of Baal, Persian Chamber, Queen Esther's Cave) and in Mammoth Cave (Oolite Cavern, The Oval, and Pisa Chamber). Apart from commenting on the size and shape of these features (a height of 45 m being cited for the Temple of Baal by Dunlop 1979) there is little or no comment about their origin in the literature. Dunlop (1979) described the Persian Chamber as "a deep, symmetrically scoured pothole" and, in the absence of any contrary explanation, this has been taken by some cave guides to mean that the cupolas were eroded by vast underground whirlpools. This explanation, however, does not accord with the available evidence.

Another possible explanation for the development of cupolas would be to attribute

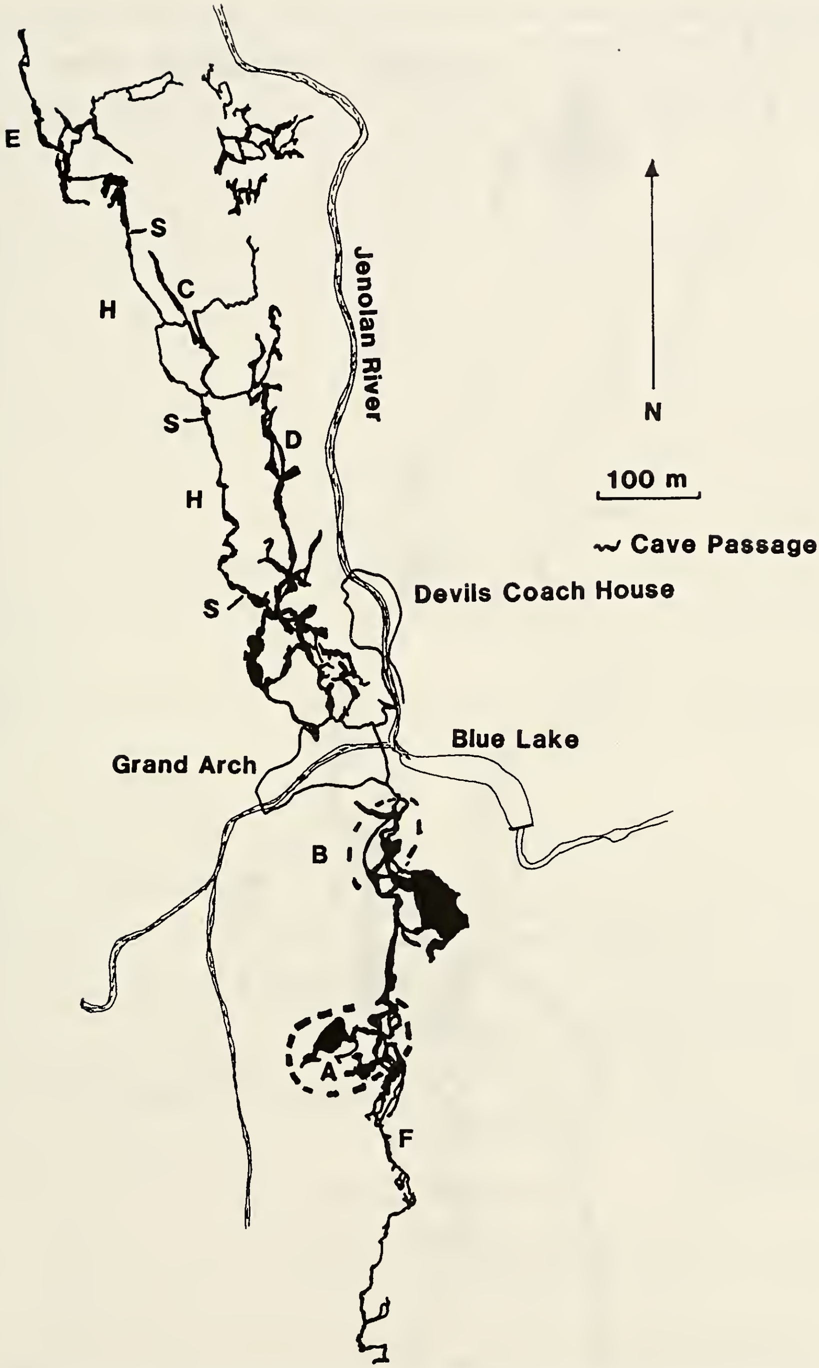

Figure 4. Simplified map of the Jenolan Tourist Cave System after unpublished compilation map by K. Oliver. A) Southern, Orient-Baal-River Cupola Cluster; B) Northern, Cerebus-Cathedral Cupola Cluster; C) Jubilee Cave; D) Imperial Cave; E) Spider Cave; F) Barrelong Cave; H) Halls in the Jenolan Underground River; S) Sumps in the Jenolan Underground River.

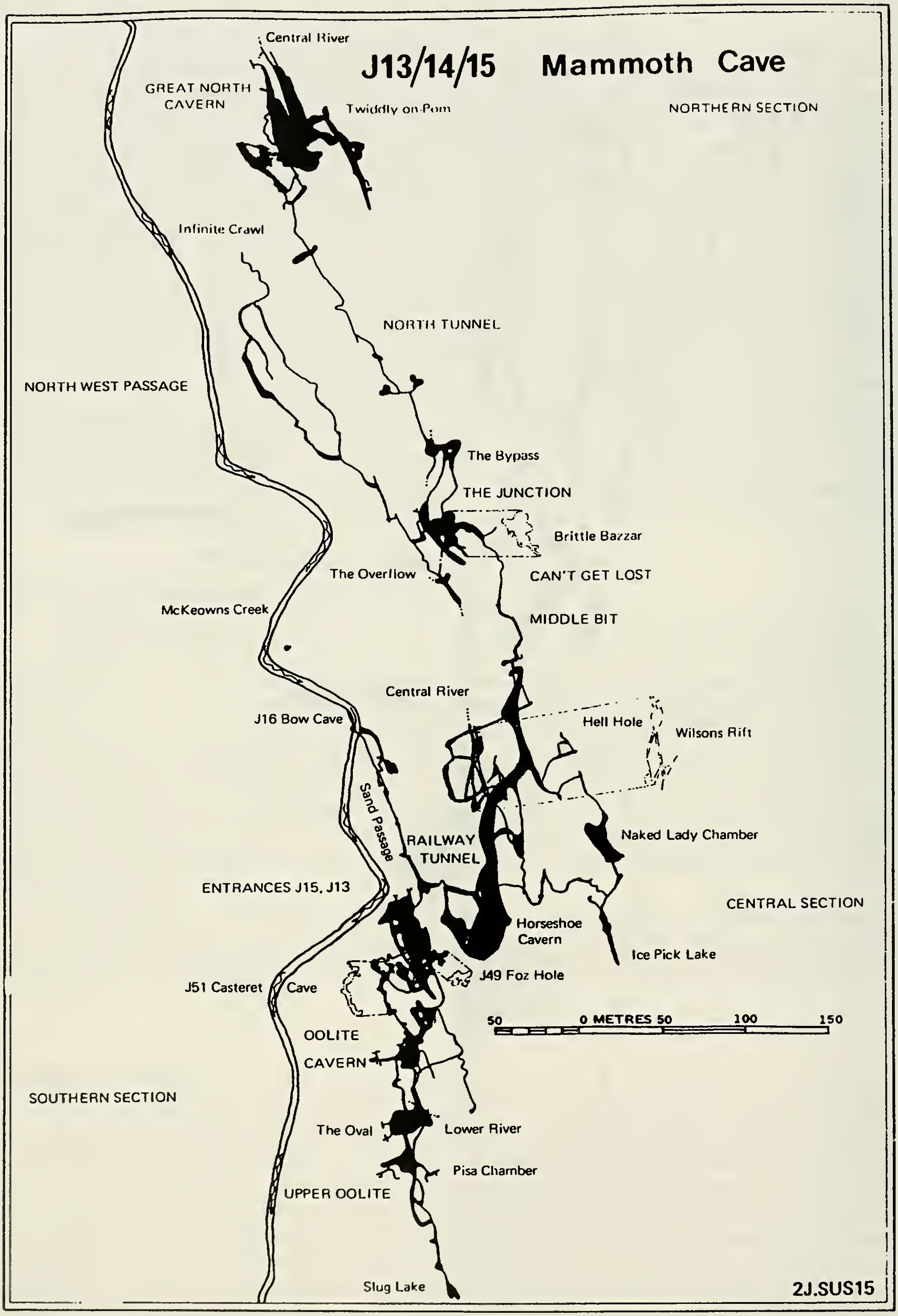

Figure 5. Mammoth Cave, after Welch (1976). Note location and distribution of cupolas; Pisa Chamber, The Oval and Oolite Cavern and of other isolated chambers.

them to mixing corrosion or convection in meteoric water. Dublyansky (1980) noted that cupolas produced by these types of processes show deep penetration into a guiding joint. While some small-scale cupolas at Jenolan do show penetration into guiding joints or bedding planes, the ceilings of the large cupolas do not penetrate into structural planes in the limestone, but truncate them. The large cupolas are therefore unlikely to have been produced by mixing corrosion or convection currents in meteoric water.

There does not appear to be any discernible pattern to the distribution of cupolas within the cave system, nor does there appear to be any obvious genetic relationship between the cupolas and the cave passages with which they connect. In the southern show caves cupolas occur in two distinct clusters, a southern Orient-Baal-River cluster (A in Fig. 4) and a northern Cerebus-Cathedral cluster (B in Fig 4). The low-level connection between the Orient-Baal-River cluster and Lucas Cave appears to have formed after the cupolas. In Mammoth Cave (Fig. 5) cupolas such as Pisa Chamber, The Oval and Oolite Cavern are connected by lower-level passages that have been guided by geological structures and appear to have formed after the two cupolas.

Halls are elongate structurally guided cavities named after Caesars Hall in Wyanbene Cave, New South Wales (Osborne, 1996). The height of halls generally exceeds their width and they either have blind terminations along strike or are partially closed along strike by significant constrictions called "narrows". The passages through which the Jenolan Underground River flows between sumps are examples of halls (e.g. the Imperial Streamway, H in Fig. 4) and the sumps in the river are narrows ("S" in Fig 4). I (Osborne 1993, 1996) described how vadose weathering of unstable minerals resulted in halls being exhumed, but did not explain how the halls formed in the first place.

Any new synthesis must account for origin and distribution of cupolas and halls and how they were able to form before the passages that now connect them to the cave system as a whole.

Conduits with Wall Niches

Cave passages with a roughly rectangular cross-section, often 6 m high by 3 m wide, are found in a number of parts of the cave system (e.g. Madonna Cave in Chifley Cave, the Tower Chambers-Pool of Reflections passage, Fig. 6, and Mons Meg in River Cave). These passages have essentially flat ceilings that have been cut directly across bedding. A series of curved indentations are developed in the walls of these passages. The uppermost indentation is usually the widest. The passage floor is frequently sediment; however, in rare cases there is a sloping bedrock floor with a narrow, sometimes meandering, slot cut in its centre. Both Kiernan (1998a) and I (Osborne 1987) interpreted these passages as large phreatic conduits in which later vadose incision had cut deep, wide floor canyons. The floors and ceilings of these passages rise and fall in a loop-like fashion. This was interpreted as evidence for the development of phreatic loops.

This interpretation however ignored some simple facts:

i. Where the floors rise they are often made of sediment, not bedrock

ii. The passages are developed in almost vertically bedded limestone (unlike passages of similar cross-section shown in textbooks)

iii. The wall niches do not slope gently downstream, as would be expected if they resulted from vadose incision, but instead rise and fall in fold-like patterns.

Any new synthesis must account for the origin of these striking passages. Recently I (Osborne 1999) proposed an alternative interpretation of these passages involving paragenesis (see below).

Figure 6. Section of loop between Pool of Reflections and Tower Chambers, River Cave, looking north. Note niches and planes of repose in right (eastern) wall. Second niche above path rises towards, and then falls after bend in path. Narrow slot in floor is visible to the left of path in mid-field.

Secondary Mineralisation of Palaeokarst and Bedrock, Deposition of Coarse Calcite Crystals and Emplacement of Dolostone

I have described how weathering of pyrite-bearing dolomitic palaeokarst deposits at Jenolan Caves resulted in ancient filled cave passages being exhumed (Osborne 1984, 1991, 1993, 1996). I noted that aragonite and sulfate speleothems were preferentially deposited on a substrate of weathering dolomitic palaeokarst (Osborne 1994). It was proposed that dolomitisation and pyrite emplacement could have been caused by basinal fluids originating in the Sydney Basin sequence which overlay the Jenolan Caves Limestone for much of the Mesozoic and into the Tertiary.

Recent detailed fieldwork has shown that there are three distinct types of yellow-coloured dolomitic material exposed in the caves:

i. dolomitised and pyritised bedrock structures (e.g. algal mats),

ii. dolomitised and pyritised laminated carbonate and crinoidal calcarenite palaeokarst, and

iii. cavity-filling crystalline dolostone.

All three types of dolomitic material occur as remnant deposits and form roof pendants in the caves.

Some of the material previously interpreted as dolomitised palaeokarst has now been found to be either dolomitised bedrock or crystalline dolostone. Dolomitic roof pendants in Ribbon Cave, formerly thought to be dolomitised palaeokarst, have now been found to be algal mats in the bedrock which have been dolomitised. The dolomitic palaeokarst I (Osborne 1993) described as being exhumed from Barrelong Cave (F in Fig. 4) and some of the dolomitic roof-pendants near the Pool of Cerebus (Fig. 7) have now been found to be cavity-filling crystalline dolostone.

While the dolomitised bedrock and palaeokarst deposits are the result of an alteration process, the crystalline dolostone fills spar-lined voids or is separated from bedrock by a zone of ferruginous alteration. This suggests that it was deposited in preexisting cavities.

In a number of places, particularly in the northern part of Imperial Cave (D in Fig. 4), cave passages intersect masses of coarse calcite crystals. These crystals line cavities, which in places have open cores. I interpreted these crystals as palaeokarst deposits (Osborne 1984, 1991). Crystals with a similar habit are found both as wall coatings and lining open cavities in River Cave and Oolite Cavern, Mammoth Cave. In River Cave the crystals overlie both bedrock and laminated carbonate palaeokarst and in places the crystal-lined cavities are filled with crystalline dolostone (Fig. 8).

Any new synthesis must account for the alteration of the bedrock and carbonate palaeokarst, the excavation of the cavities into which the crystalline dolostone was deposited, the deposition of the coarse calcite crystals and the deposition of the crystalline dolostone.

Deposition of Aragonite, Dolomite and Sulfate Speleothems

Some of the most highly regarded speleothems in Jenolan Caves are composed of aragonite (Fig. 9). The deposition of aragonite speleothems in caves is usually attributed to the "poisoning" effects of magnesium ions on the calcite crystal lattice (Hill and Forti 1997). Work in progress with R. Pogson and D. Colchester of the Australian Museum has found that magnesium-rich phases, huntite, dolomite and ferroan dolomite have been and continue to be deposited in close association with the aragonite speleothems.

The Jenolan Caves Limestone, however, contains little magnesium and almost no pyrite. Of two bulk analyses reported by Carne and Jones (1919), one shows a "trace" and the other a nil result for $MgCO_3$. I noted the close association between the aragonite

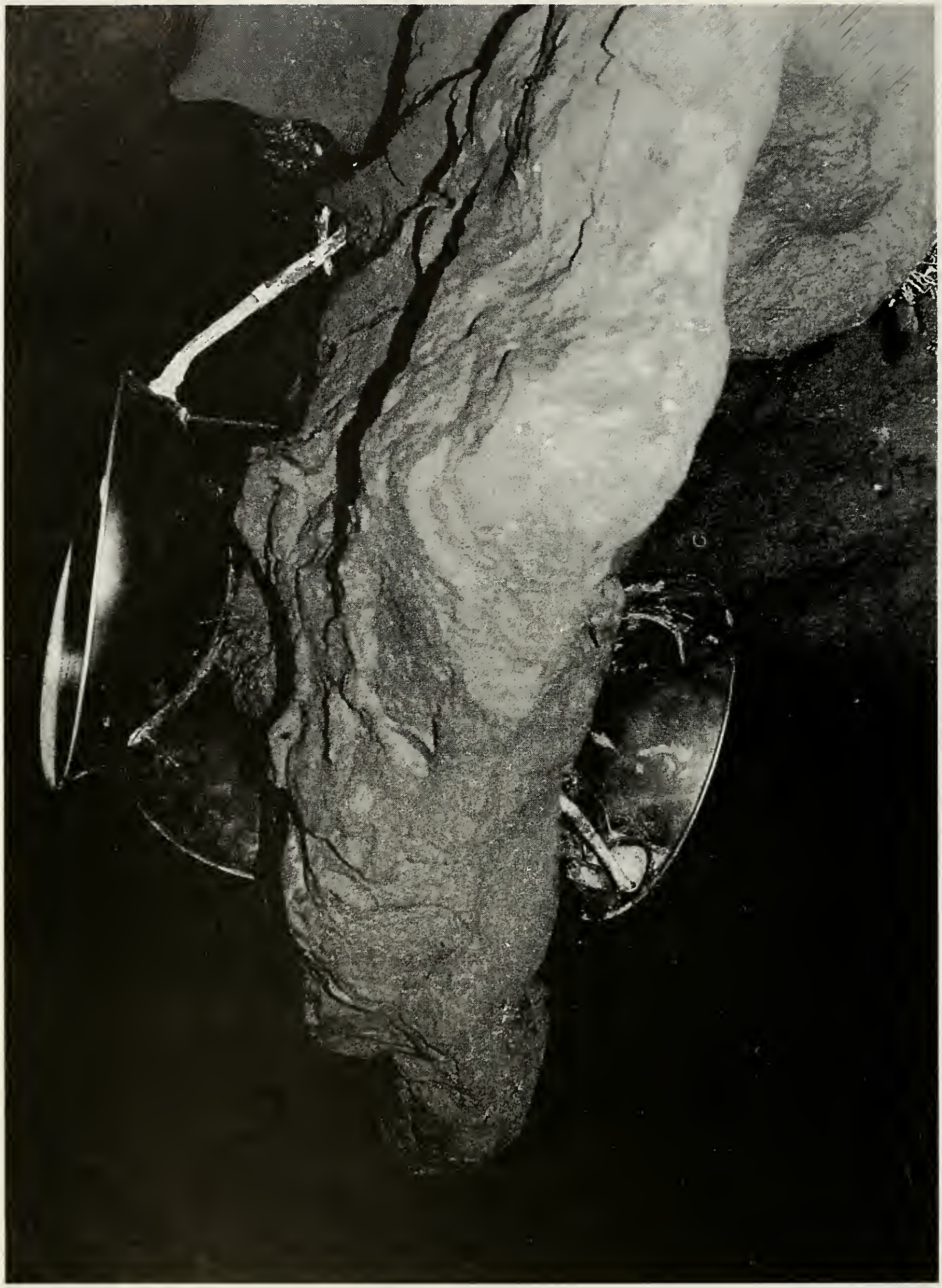

Figure 7. Roof Pendant of crystalline dolostone, adjacent to Pool of Cerebus, Pool of Cerebus Cave. Circular artifacts are light reflectors. Note small complex aragonite speleothems in upper left and right of photo.

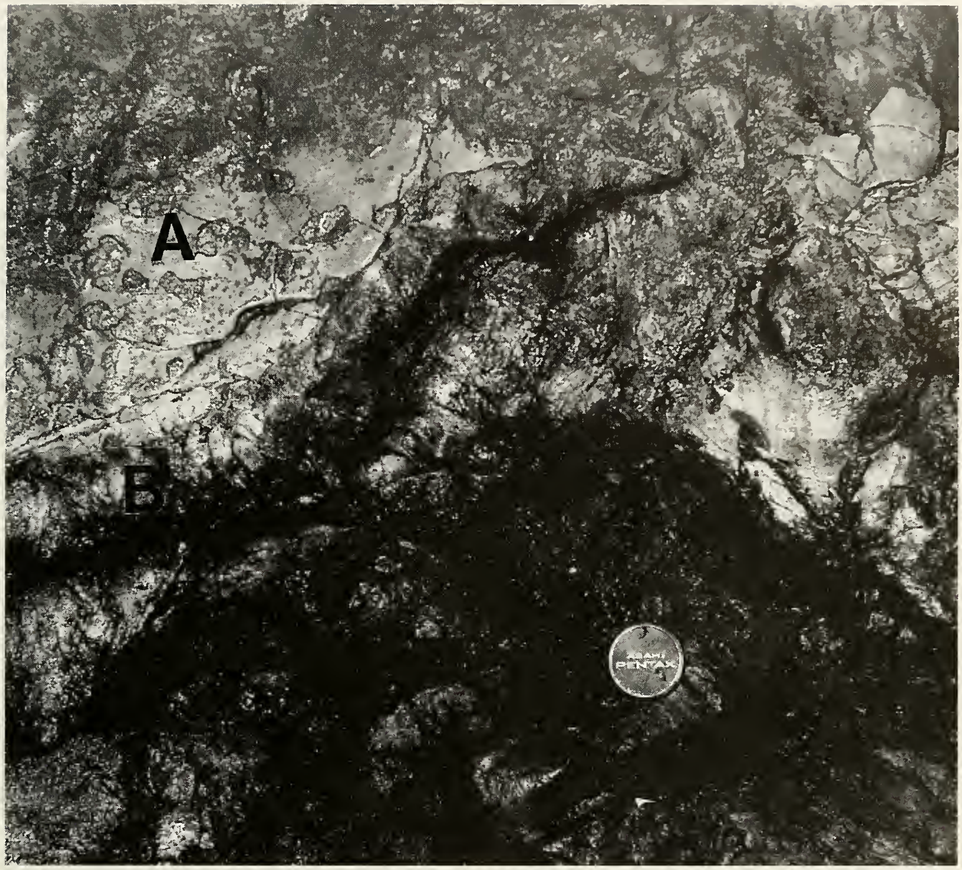

Figure 8. Calcite crystal vugh filled with crystalline dolostone, base of cave wall, Mud Tunnels area, River Cave. A= coarse spar lining, B= host rock, lens cap is resting on yellow dolostone. Lens cap 50 mm

and sulfate minerals and deposits of dolomitic palaeokarst (Osborne 1994). Weathering of the dolomitic palaeokarst and dolostones is the most likely source of the magnesium, and weathering of secondary pyrite the most likely source of the sulfate. The continuing deposition of huntite, dolomite and ferroan dolomite, usually associated with evaporative conditions, in the extremely wet conditions of Ribbon Cave requires further investigation and explanation.

ELEMENTS OF A NEW SYNTHESIS

My aim here is to identify those factors and processes that may account for the particular features and characteristics of Jenolan Caves. These factors will then be used to form the elements of a new synthesis and framework chronology. Much of the evidence for these factors and processes is derived from observations in the southern show caves and their major southerly extension, Barrelong Cave. It has proved much more difficult to unravel the events and processes that have occurred in the northern show caves due to the volume and complexity of fluvial sediments in them, which obscures evidence for other processes.

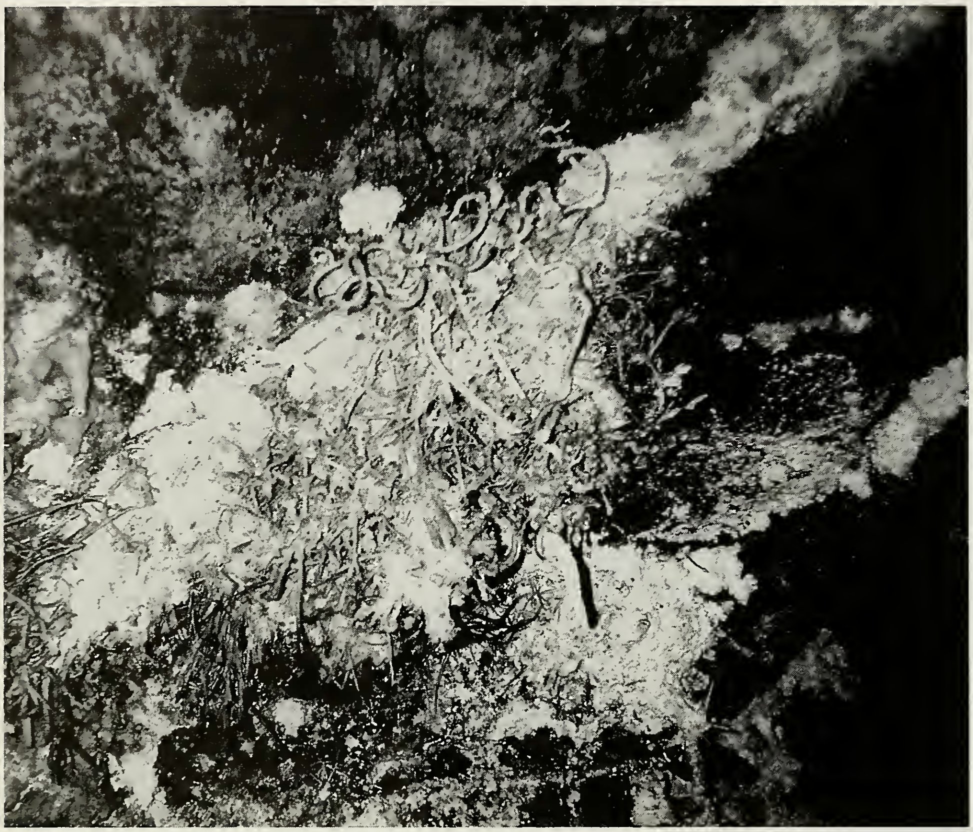

Figure 9. The Lyrebirds Nest, a complex aragonite helictite, Ribbon Cave. Spirals and spikes are aragonite; white cauliflower-like growths are composed of huntite in a pasty from, similar to ricotta cheese.

Multiple Karstification

Jenolan Caves are not the product of a single recent event during which a single process operated, but, rather, are the product of a number of different events, during which a variety of processes operated. These events took place over a geologically significant period of time (Osborne 1984).

The features we see in the caves today can only be understood, and the evolution of the caves deciphered, if we recognise from the outset that they result from the overprinting of a range of different events and processes. It is clear that unraveling these events is, and will continue to be, difficult, requiring a very significant commitment to detailed field investigation.

Hydrothermal/Per Ascensum Processes

Conventional models for the excavation of limestone caves (speleogenesis), e.g. Ford and Williams (1989), have stressed the dominant role of meteoric water sinking into the limestone (per decensum) as the agent of solution. Recently there has been increasing discussion in the international literature about the role played in speleogenesis by hydrothermal, artesian and interstratal waters; that is water rising into the limestone body from below (per ascensum). Dublyansky (1980) listed four morphological criteria that strongly indicate a hydrothermal origin for caves.

1. They lack a genetic relationship to the surface topography.
2. They are largely or entirely devoid of fluvial sediments.
3. They display a three-dimensional rectilinear maze form guided by major fracture systems and, more rarely, by bedding planes, indicative of excavation by slowly flowing ascending waters.
4. The highest parts may display cupola-form solutional pockets.

While morphological characteristics are indicative of non-meteoric origins, the most reliable indicators of a non-meteoric origin are; high temperature minerals, clay minerals deposited in low pH conditions (Hill 1987; Hill and Forti 1997 and Forti 1996), stable isotope ratios and fluid inclusion thermometry (Bakalowicz et al. 1987 and Cilek et al. 1994).

Ford (1995) stated that caves formed by meteoric waters flowing downwards are the global norm, while ascending (per ascensum) waters and gases create few caves. He noted that per ascensum caves are more likely to intersect or be guided by palaeokarst than meteoric caves.

Many of the world's largest and most spectacularly mineralised caves, e.g. Carlsbad (Hill 1987) and Lechuguilla Cave, New Mexico, Wind & Jewel Cave South Dakota (Bakalowicz *et al.* 1987) and the gypsum caves of the Ukraine (Klimchouk 1996), are now thought to have formed by the action of rising hydrothermal or artesian waters. Significant hydrothermal caves occur in Hungary and the Czech Republic. The role played by hydrothermal processes in the development of the World Heritage Listed Ochtinská Aragonite Cave in Slovakia remains controversial (Cilek *et al.* 1997).

While much research internationally has focused on caves that have formed solely or principally by hydrothermal or artesian processes, Ford (1995) noted that "multi phase cave systems of the general character of meteoric-hydrothermal-meteoric are probably far more common than generally realised".

Jenolan Caves are clearly not solely the product of hydrothermal or artesian processes. Many of the unusual features of the caves such as intersection of palaeokarst, formation of cupolas and halls, alteration of bedrock and palaeokarst and the deposition of coarse calcite crystals and crystalline dolostones probably, however, result from one or more phases of per ascensum hydrothermal /artesian development.

Studies that could provide more direct evidence for the role of hot or warm non-meteoric water have only just begun. Reconnaissance fluid inclusion investigations suggest that the waters depositing the coarse calcite crystals were neither particularly saline, nor very hot, and suggest, along with the available mineralogical evidence, that the per ascensum processes at Jenolan may have been somewhat different from those described from North America and central Europe.

Inception Horizons

The inception horizon hypothesis (Lowe 1992; Lowe and Gunn 1997) seeks to explain the development of the initial conduits in karst rocks from which caves later develop. It postulates that initial conduits are most likely to form in particular lithostratigraphic features called inception horizons. Lowe (1992) defined inception horizons as "any lithostratigraphically controlled elements of a carbonate sequence that passively or actively favours localised inception of dissolutional activity, by virtue of physical, lithological or chemical deviation from the predominant carbonate facies within the sequence."

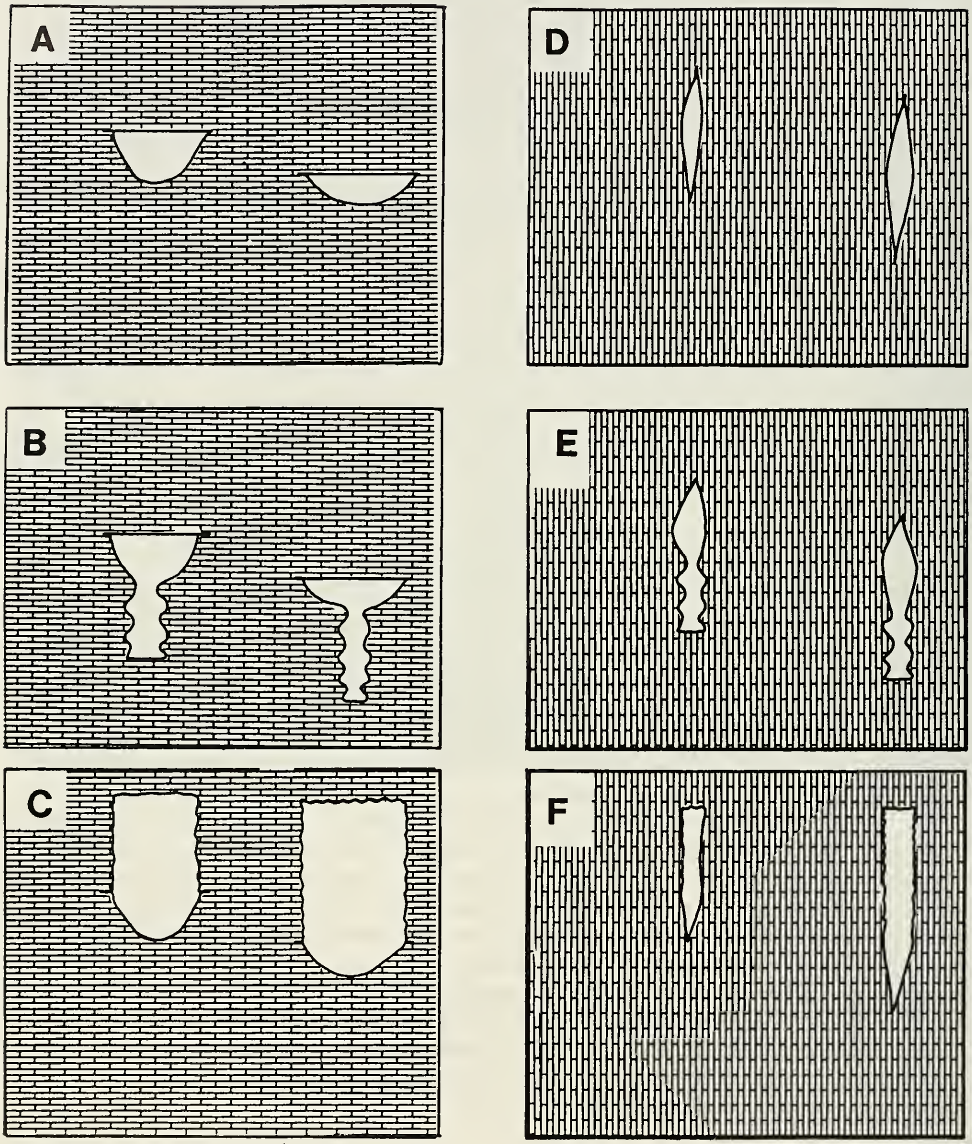

Figure 10. Cross-sections showing development of passages in horizontal and steeply-dipping limestone after Osborne (1999a). A, B and C = horizontally-bedded limestone. Thick horizontal lines are inception horizons. A) Elliptical phreatic passages developed below inception horizons, axis of ellipse is horizontal, parallel to bedding; B) Keyhole passages produced by vadose incision in floor of phreatic passages. Axis of canyon is perpendicular to bedding. C) Paragenetic development of ovate phreatic passages excavates upwards, above the level of the inception horizons. Result is broad passage with wall morphology influenced by variable solubility of bedding. D, E and F = steeply-dipping limestone. D) Elliptical phreatic passage developed in steeply-dipping limestone. Axis of ellipse is vertical, parallel to bedding; E) Keyhole passages produced by vadose incision at lowermost point of phreatic passage. Axis of canyon is parallel to bedding; F) Paragenetic development of ovate phreatic passages excavates upwards producing conduit with relatively planar walls, guided by bedding.

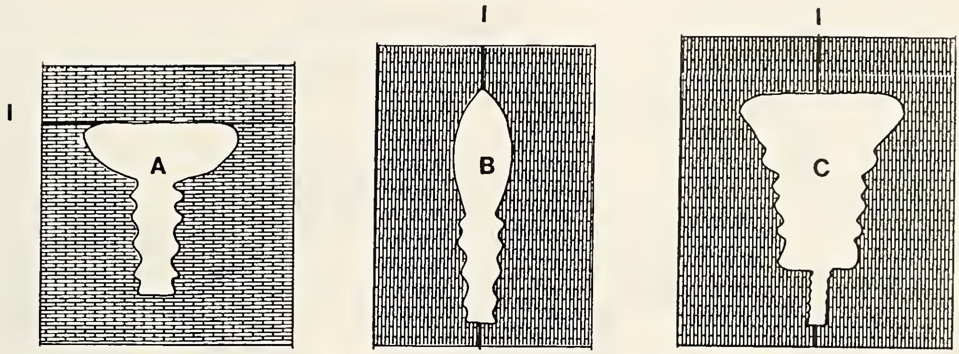

Figure 11. Comparison of 3 passage cross-sections after Osborne (1999). I = inception horizon. A) "Keyhole" passage in horizontally-bedded limestone, consisting of upper elliptical phreatic pressure tube with long axis parallel to bedding and lower vadose canyon with axis normal to bedding; B) Passage of similar origin developed in vertically-bedded limestone. Note upper phreatic pressure tube with long axis parallel to bedding and lower vadose canyon with axis parallel to bedding; C) Paragenetic conduit as found at Jenolan Caves. Note similarity of profile to that of "A". Small "canyon" in floor is remnant of initial passage prior to partial blockage and paragenesis. Upper section of passage developed as a stable perched water level was established above the sediment pile following cessation of sedimentation and before incision.

Like most research and discussion about the formation and development of limestone caves, Lowe's work has been largely concerned with phenomena occurring in horizontal to gently dipping limestone. I (Osborne 1999) have recently discussed how inception horizons may behave in limestone that is vertically to steeply dipping. While it is clear that bedding does play a role in guiding cave development at Jenolan, there has yet to be any detailed study of the lithostratigraphic features that initiated and guided cave development there.

Morphology of Caves Developed in Steeply Dipping Limestone

Most textbook diagrams showing cave cross-sections and their likely origin (e.g. Figure 52 of Jennings 1985) assume that the limestone has horizontal or near-horizontal bedding. At Jenolan, however, the bedding is steeply dipping and close to vertical, making these diagrams, and the inferences attached to them, inapplicable.

Figure 10, after Osborne (1999), shows some of the differences in cave cross-section that are likely to occur when caves develop in vertical to steeply dipping, rather than horizontally-bedded limestone. Phreatic tubes in vertical to steeply-bedded limestone will be ovoid with vertical axes of symmetry and tubes incised by vadose canyons will not have the classic keyhole shape as found in horizontally-bedded limestone. Passages developed in steeply-dipping limestone that have the same or similar cross-section to those shown in the classic text book diagrams (Fig. 11) are most likely not to have been produced under the same conditions. As a consequence previous assumptions made that passages at Jenolan are either vadose, phreatic, pressure tubes or canyons etc. all require detailed reevaluation.

Sediment Blockages and Flow-Shifting

In impounded karsts, like Jenolan, water sinking into the karst drainage system carries with it significant amounts of insoluble sediment such as mud, sand, gravel and cobbles derived from the surrounding non-limestone catchment. At Jenolan the sediment

Figure 12. Cross-section of southern show caves after Trickett (1925).

contains considerable quantities of quartz sand and volcaniclastic cobbles and boulders. I proposed that in impounded karsts with steeply to vertically dipping limestone, major flow paths for water through the limestone could become blocked with sediment, shifting flow from below ground to the surface (Osborne 1999).

During periods of blockage the stream will shift to the surface and then could incise into the limestone producing gorges that parallel (and in places intersect) former underground flow paths. This process may account for the contradictory evidence for landscape age given by the presence of high-level gravels of differing ages at the same elevation. A relatively recent blockage of the Grand Archway could result in the valley upstream being filled with sediment to the level of the saddle. Young fluvial sediment could then be deposited on the saddle adjacent to, and at the same level as, much more ancient sediment which was deposited well before the limestone became breached by the Grand Archway.

Following the blockage the stream may again be captured underground by the same inception horizon at a level below that of the blockage, providing another mechanism for intersection of palaeokarst by more recent caves.

Paragenesis

Paragenesis, described by Renault (1968), is the process of limestone dissolution at the upper limestone-water interface above an accreting sediment mass in a cave. As the sediment continues to be deposited, water is forced upwards against the passage ceiling which it dissolves away. As a consequence paragenetic passages tend to have relatively flat ceilings. As solution proceeds above the accreting sediment, lower sections of the walls are protected from solution by the sediment, resulting in the development of an inward-sloping planar profile in the lower wall, above which sideways dissolution produces a concave wall niche. Lange (1963) and Goodman (1964) called these inward-sloping planes in the lower walls of passages “planes of repose”.

By forcing aggressive water up against the cave ceiling, paragenesis allows relatively small and slow water flows to produce high cave passages with a large cross-section. Osborne (1999) proposed that the large conduits with wall niches at Jenolan (Fig.

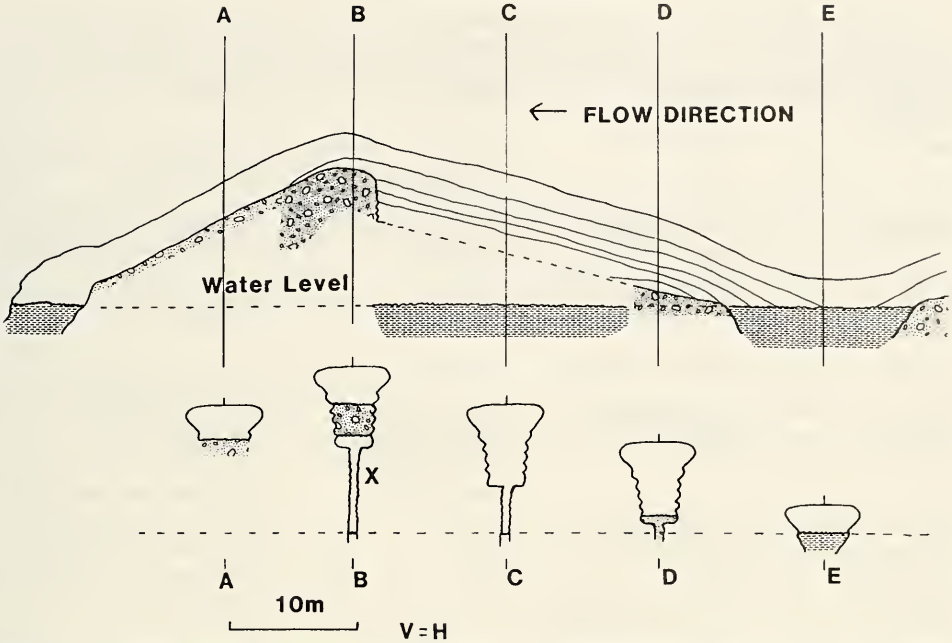

Figure 13. Development of paragenetic loop, based on passage shown in Figure 7, north of Pool of Reflections, River Cave after Osborne (1999a).

11) are not the result of large phreatic flows followed by massive incision, but are exhumed paragenetic passages.

The rising and falling wall niches and the apparent "phreatic loops" are now interpreted as paragenetic in origin. The idea that the passages in River Cave were phreatic loops probably had its origin in the cross-section provided by Trickett (1925)(Fig. 12) which shows Mons Meg as a large loop. Trickett did not show, however, that the floor of this loop consists of sediment extending to a great depth, rather than bedrock, which a simple reading of his section might imply. Observations in the Tower Chambers-Pool of Reflections passage in River Cave (Fig 13) showed that these loops are better interpreted as paragenetic features, resulting from the partial blockage of an original passage.

If the large conduits are paragenetic in origin there is no need to infer that significantly larger underground stream flows occurred in the past.

Vadose Weathering and Secondary Mineralisation

Deposits emplaced in hydrothermal cavities are likely to contain minerals, such as pyrite, which will decompose when exposed to oxygenated vadose seepage water. I proposed that weathering and underhand stoping of deposits that are unstable in vadose conditions are significant mechanisms for the exhumation of some large chambers (halls) in eastern Australian caves (Osborne 1996). It was also recognised that this process was currently taking place in parts of the Barrelong Cave and in the Imperial Streamway at Jenolan.

There is increasing evidence to suggest that stoping of hydrothermal deposits is widespread at Jenolan. Evidence for both past and presently active stoping is found in

TABLE 1.

A Framework Chronology for Jenolan Caves

Geological Era/Period	Phase	Event/Process	Feature	Example
Present	10	Stability	Low Mg Calcite Speleothems Continued Weathering Mg Rich Minerals	Orient Cave Ribbon Cave Ribbon Cave
Quarternary	9	Meteoric Speleogenesis 5 Exhumation	Nick Point Sediment Cliffs Breakdown	The Ladder, River Cave Exhibition Chamber, Lucas Cave
A number of Cainozoic Phases	8	Meteoric Speleogenesis 4 Paragenesis	Conduits Loops	The Slide, Lucas Cave Mons Meg, River Cave
? Tertiary	7	Meteoric Speleogenesis 3	Invasion Caves	Baal-River Passage
? Late Cretaceous	6A	Hydrothermal Speleogenesis 2 Hydrothermal Fills & Alteration	Crystal-lined Cavities Dolomitic Crystal Altered Algal Mats Altered Palaeokarst Non-Detrital Clay	Mud Tunnels, River Cave Pool of Cerberus Cave Ribbon Cave Olympia Steps, Ribbon Cave River Lethe, River Cave
? Late Cretaceous	6	Hydrthermal Speleogenesis 2 Evacuation	Cupolas Halls Tubes	Persian Chamber, Orient Cave Jenolan Underground River Ribbon Cave
Permian	5	Cave fill & Landscape Burial	Fluvial Sediments	Dreamtime Cave
Permian	4	Metereoric Speleogenesis 2	Large Caves	Dreamtime Cave
? Early Permian	3	Hydrothermal Speleogenesis 1	Crystal-lined Cavities	Lucas Cave Entrance
? Latest Carboniferous	2	Marine Transgression and filling	Crinoidal and Laminated Carbonates	Olympia Steps, Ribbon Cave
? Late Carboniferous	1	Meteoric Speleogenesis 1	Phreatic Caves	Olympia Steps, Ribbon Cave

some cupolas and in smaller passages, such as those in the western parts of Pool of Cerebus Cave.

The role of the hydrothermal dolostones and altered rocks containing dolomite and pyrite as substrata and sources for aragonite and sulfate speleothems is now more clearly established, however it is equally clear that this is not the whole story and that much more work is needed in this area.

A FRAMEWORK CHRONOLOGY

The chronology presented below is the first attempt to bring together the ideas I have previously published about the likely age of palaeokarst at Jenolan (Osborne 1995) and the mechanisms discussed above. The aim is to produce a framework chronology for the development of Jenolan Caves, which can form the basis for subsequent investigation and discussion. Jenolan Caves have a complex history. It is more likely than not that many of the events described here as occurring once, will, with further examination, be found to have taken place on a number of occasions during the hundreds of millions of years that caves have existed in the Jenolan Caves Limestone.

It is highly likely that there have been many phases of sediment blockage leading to flow shifting and paragenesis during the Cainozoic history of the caves. There is some evidence to suggest that two or more hydrothermal/per ascensum phases have occurred. I have indicated in the sub-heading of each phase the type of process involved and a number to indicate the number of times each process has taken place in the chronology. A summary of the chronology is given in Table 1.

Maximum Age of Karstification

Convincing evidence for karstification of the Jenolan Caves Limestone prior to the Kanimblan Orogeny has yet to be found, however recent fieldwork has identified possible solution cavities which appear to predate significant folding. All confirmed palaeokarst features so far described have an angular unconformity at their boundary with the Late Silurian Jenolan Caves Limestone and show no sign of having been effected by either Tabberabberan (Mid Devonian) or Kanimblan (Early Carboniferous) folding.

Phase 1 Meteoric Speleogenesis 1

This phase of cave development produced a major phreatic conduit in the south, now filled and exposed in Barrelong and River Caves, and a network of smaller passages now filled and exposed in the Grand Archway, Devils Coach House and in surface exposures.

While it is difficult to come to any definitive conclusion about the nature and extent of this period of speleogenesis, the conduit in the south suggests the excavation of a significant phreatic cave system more than 100 m below the likely surface level. There is no evidence of vadose development.

Phase 2 Marine Transgression and Filling

Marine carbonate sediments forming a sequence of crinoidal grainstones and graded-bedded lime mudstones filled the phase 1 caves. Detrital quartz is absent from these rocks which have been altered by the emplacement of secondary pyrite and dolomite. They are disconformably overlain by pyrite-bearing conglomerates in Arch Cave. Similar deposits are found at Bungonia Caves (N.S.W.) and Ida Bay (Tasmania) (Osborne 1995).

While there is no direct evidence for the age of these units, I argued that they are most likely Latest Carboniferous (Osborne 1995). The transgression must have occurred prior to deposition and filling of the Camp Creek and Jenolan River palaeovalleys by conglomerates of the Permian Snapper Point Formation. This may be a previously unrecognised event for which palaeokarst deposits are the only remaining evidence. Preliminary palaeomagnetic work by Dr Brad Pillans of the Research School of Earth Sciences, Australian National University, has confirmed that these strata have not been folded and are older than Latest Cretaceous.

Phase 3 ? Hydrothermal Speleogenesis 1

A spar-lined cavity, filled with carbonate-cemented sandstones and conglomerates containing secondary pyrite, is exposed in the entrance area of Lucas Cave. The spar is similar in habit to that found filling cavities in River and Imperial Caves, but is white in colour and not associated in any way with ferroan dolomite. Since the pyrite in the sandstone is thought to be a product of a later hydrothermal event (phase 6) it is possible that there may have been an early, possibly Permo-Carboniferous, phase of hydrothermal cave development. There is some other evidence also suggesting an early phase of hydrothermal development, but it requires much further investigation.

Phase 4 Meteoric Sepeleogenesis 2

Phase 4 caves developed at Jenolan prior to the deposition of the conglomerates in the Surveyors Creek and Jenolan River palaeovalleys. Although remnants of these caves are more difficult to recognise than phase 1 caves, their palaeogeographic relationships are much clearer. Phase 3 caves formed below the level of the 900 m bench and consist of large conduits such as Dreamtime Cave with cross-sectional shapes strongly suggestive of paragenesis (Osborne 1995). These types of passages are consistent with development in a sediment-rich, high relief, fluvio-glacial depositional environment such as that associated with the Permo-Carboniferous Talaterang Group and the Permian Snapper Point Formation (Herbert 1972, 1980).

Phase 5 Cave Filling, Valley Filling and Burial

Phase 3 and 4 caves are filled with sandstones and conglomerates in which secondary pyrite has been emplaced. In addition to Dreamtime Cave, strongly-cemented pyrite-bearing conglomerates and sandstones are exposed at the surface in the saddle above the Grand Archway and underground in the northern parts of Lucas Cave (e.g. Wiburds Dig), in Arch Cave, Chifley Cave and Elder Cave.

These sediments are likely to represent the earliest stage of valley-filling associated with Sydney Basin sedimentation. As with other valley-fills in the Jenolan Caves area (Bembrick 1980), they should be included in the Late Carboniferous or very Early Permian Talaterang Group (Gostin & Herbert 1973). After the caves and valleys became filled, there seems to have been a general cloaking of the landscape by Permian strata such as the Snapper Point Formation. This would have buried the whole of the limestone mass. The period of burial is likely to have extended from the Mid Permian through most of the Mesozoic.

Phase 6 Hydrothermal Speleogenesis 2

At least one major hydrothermal, per ascensum, phase of cave development followed phase 5. This was responsible for the excavation of three types of void; cupolas (circular in plan), halls (rectangular to lens-shaped in plan) and tubes (passages with roughly circular cross-section). Halls were produced where hydrothermal excavation occurred along inception horizons. The rising water was able to excavate upwards, penetrate through and expose palaeokarst fills, which would have prevented the passage of descending meteoric water.

Cupolas, halls and tubes were filled with coarse calcite crystals, ferroan dolomite, clays and iron-rich phases. Secondary pyrite and dolomite were emplaced by the rising fluids in the sediments filling the phase 1, 3 and 4 caves.

Examples of phase 6 cavities include:

Cupolas:	Queen Esther's Chamber, River Cave
	The Temple of Baal
	Persian and Egyptian Chambers, Orient Cave
	Mud Tunnels, River Cave
	Cathedral, Lucas Cave
	Queens Diamonds, Imperial Cave
	Oolite Chamber, Mammoth Cave
Halls:	Imperial Streamway
	Barrelong Cave
Tubes:	Barrelong Cave (see Osborne 1993)
	Ribbon Cave
	Passages in River Cave near the Junction
	Pool of Cerebus west, near Arabesque

This phase could have occurred at any time between the mid Permian and the initiation of the present phase of landscape development (Late Cretaceous to Early Tertiary), however there is yet no direct evidence for its timing. It could well be related to thermal activity associated with the Late Cretaceous uplift of the Eastern Highlands and the opening of the Tasman Sea.

Phase 7 Meteoric Speleogenesis 3 Invasion Meteoric Caves

Following the uplift of the Eastern Highlands most of the Snapper Point Formation was eroded from the high parts of the landscape and the Talaterang Group conglomerates were exhumed from the Jenolan River and Camp Creek valleys. Meteoric water was then able to enter the Jenolan Caves Limestone via those inception horizons (or levels within inception horizons) that were not blocked by deposits emplaced during phases, 2, 5 and 6.

When the phase 7 passages formed below hydrothermal cavities filled with pyrite-bearing deposits, the process of exhumation by vadose weathering was initiated. Ferroan dolostone and other deposits in the cupolas began to weather and the cupolas became sediment traps. Caves also began to form along horizontal inception horizons in the Carboniferous carbonate palaeokarst, particularly where more open beds had formed the focus for pyrite emplacement.

Examples of phase 7 cavities include:

Barrelong Cave where it is developed in palaeokarst

The Baal Dig and Baal-River connection

The tourist path passages in Imperial Cave

Phase 8 Meteoric Speleogenesis 4 Paragenesis

Eventually the phase 7 caves were able to capture most of the flow of the Jenolan River and Camp Creek underground. The geometry of the system, with its lack of a simple stream path, the presence of now open cupolas acting as sediment traps and the high sediment load in the surface streams resulted in the caves becoming blocked.

Blockage of the Grand Archway resulted in the valley upstream of the being filled by sediment and water being re-directed over the Grand Arch saddle. Partial blockage of the subterranean pathways in the northern caves resulted in significant incision into the bed of the Jenolan River, as its underground capture became less and less efficient.

In the many parts of the caves large paragenetic conduits and paragenetic loops developed as local groundwater levels rose and water slowly flowed over the blockages.

Examples of phase 8 cavities include:

Conduits: The Slide, Lucas Cave
Lucinda Cave, Lucas Cave
Madonna Cave, Chifley Cave

Loops: Mons Meg, River Cave
Pool of Reflections — Tower Chambers, River Cave

Phase 8 was most likely not a single event. It is highly likely that a whole series of events involving blockage, paragenesis and flow shifting occurred throughout the Tertiary and Pleistocene. Detailed stratigraphy and palaeomagnetic dating will be required to sort this out.

Phase 9 Meteoric Speleogensis 5 Exhumation

Following incision, the surface streams became recaptured along inception horizons either at a level below the sediment-blocked caves or in adjacent, lower-level inception horizons. This produced the present conduits of the Styx and the Jenolan Underground River. In places these new conduits formed below halls (Jenolan Underground River). In some parts of the system the phase 9 passages took quite a different path through the limestone to the older, higher-level caves, e.g. the stream at the southern end of Barrelong Cave.

Fills of various ages including weathered hydrothermal deposits and fluvial sediments responsible for paragenesis were excavated as downstream blockages were removed and perched aquifers within the limestone fell.

Sediments eroded back to form nick points in south at Queens Canopy and The Ladder in River Cave. A similar process may have operated in the north, e.g. at Katies Bower, but the history of filling and exhumation is far more complex in north. The major breakdown forming Exhibition Chamber and breakdown due to crystal wedging in limestone adjacent to cupolas, e.g. 2nd Persian Chamber and Orient-River Connection, probably occurred or began towards the end of this phase. This phase probably came to an end quite recently.

Phase 10 Relative Stability

The caves, at least what we can see above water level, appear at present to be in a stage of relative stability. The nick points in the paragenetic sediments have been stabilised by flowstone. Breakdown and removal of remnants of hydrothermal deposits appears to be proceeding quite slowly. Speleothem, dominantly phosphorescent calcite, but also aragonite, continues to be deposited.

DISCUSSION

Scientific Implications

The synthesis and chronology outlined above suggest that Jenolan Caves are likely to contain features and information of scientific interest that would not have been previously expected, including:

- cavities dissolved by rising water
- minerals emplaced by "hydrothermal" waters
- sediments, including clays, of hydrothermal, rather than surficial, detrital origin
- cave morphologies formed in response to steeply-dipping bedrock
- cave morphologies resulting from paragenesis

It also suggests that:

- large passages and chambers that are out of scale with the size of present streams in the caves need not be indicative of larger stream flows and higher rainfall in the past, but may result from either hydrothermal solution or paragenesis under relatively low stream flow conditions.
- excavation and removal of palaeokarst deposits has not only resulted from fluvial erosion by meteoric water under vadose conditions, but may also have resulted from solution and upward stoping by rising hydrothermal waters and/or gravity stoping following weakening due to weathering of unstable minerals, such as pyrite, in the vadose zone.

This paper is the first step towards a new understanding the geological history and evolution of Jenolan Caves. All of the processes discussed, the attempt to bring them together into a framework chronology and the original observations on which these are based require a great deal of further investigation.

It is quite clear that further progress in understanding Jenolan Caves and other similar caves in eastern Australia requires:

people able to undertake detailed field studies of features within the caves,

time in sufficient quantity for undertaking detailed fieldwork,

laboratory studies in areas such as mineralogy, isotopes, dating etc. ,

teamwork, between field workers and those undertaking laboratory studies, and

funds to make it happen.

Management Implications

Current conservation and management of Jenolan Caves, and most other limestone caves in Australia, assume that they were formed by sinking meteoric water. It follows the dictum of Kiernan that "Maintaining the hydrological system in a natural condition is the foundation stone of karst management" (Kiernan 1988b, p 43).

If many of the significant morphological (e.g. cupolas) and mineralogical features (e.g. aragonite and gypsum speleothems) of the caves are the products or by-products of past hydrothermal processes, they will require different conservation and management strategies from those applied to features produced by current meteoric solution and deposition.

The conservation and management of these hydrothermal and post-hydrothermal features is unlikely to be dependent on maintenance of hydrological conditions or water chemistry in the catchment in general. Much more emphasis will need to be given to identifying and documenting significant and vulnerable features within the caves and developing localised management strategies at a feature by feature level. This new type of management will require the sort of detailed fieldwork and documentation that is also necessary for progress in research.

Interpretative Implications

The lack of scientific research into the origins and development of Jenolan Caves has meant that there has been little scientific underpinning for interpretation. This new synthesis and chronology can form the basis of interpretation that is able to answer many of the questions asked by tourists that could not previously be addressed. Three underground rivers and giant underground whirlpools will no longer suffice. Central to any new interpretative program will be the recognition that our understanding of the caves will undoubtedly change as research progresses.

Implications for Cave Exploration

The 'cave river' theory which has guided cave exploration at Jenolan for at least 30 years has not proved particularly useful in finding new caves. The new synthesis suggests that large cupolas are likely to be distributed rather randomly through the limestone and may have little genetic relationship with and poor connections to the passages through which water currently flows. Orient Cave and The Temple of Baal were discovered by climbing up from low-level caves into cupolas. The best chance for finding new highly decorated chambers is probably to repeat this technique. Perhaps the Chief Guides at Jenolan in the late 19th and early 20th centuries, such as Vos Wiburd and Jeremiah Wilson, knew much more about the caves and how they really worked than many of us do today at the end of the 20th century.

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